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DEVELOPMENT OF FUNCTIONAL RELATIONSHIP AND TOOL REPLACEMENT CRITERIA IN ULTRASONIC MACHINING

By

ANIL KUMAR KAPOOR

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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DEVELOPMENT OF FUNCTIONAL RELATIONSHIP AND TOOL REPLACEMENT CRITERIA IN ULTRASONIC MACHINING

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

By
ANIL KUMAR KAPOOR

to the
DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR
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1.9.73

CERTIFICATE

This is to certify that the work "Development of functional relationship and tool replacement criteria in ultrasonic machining" by Anil Kumar Kapoor has been carried out under my supervision and has not been submitted elsewhere for a degree.

1.9.73

(Dr. G.S.KAINTH)
Assistant Professor
Department of Mechanical Engineering
I.I.T. Kanpur

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A.K.Kapoor

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[redacted]

NOTATIONS

ADC	:	Actual Depth Cut
AMR	:	Average Machining Rate
C	:	Concentrations
L	:	Load
MR	:	Machining Rate
t	:	Time
TWR	:	Tool Wear Rate
VDC	:	Virtual Depth Cut
VMR	:	Virtual Machining Rate

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SYNOPSIS

Material removal rate and tool wear in ultrasonic machining depends on many factors such as amplitude and frequency of vibration of tool, static load, concentration and material of workpiece. Experiments are conducted on soda glass using mild steel tool with load varying from 0.476 Kg. to 0.93 Kg. and slurry concentration (by volume) varying from 0.125 to 0.25. Emery of 120 mesh is used as abrasive. In present work, functional relationship of machining rate with load, concentration and time has been established taking other parameters constant. Functional relationship of tool wear rate with static load has also been established.

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Machining rate relationship, thus obtained, is used to find the optimal time after which the tool should be replaced. The optimal tool replacement is based on

(i) the minimum cost criterion

(ii) the maximum production rate criterion.

CHAPTER I

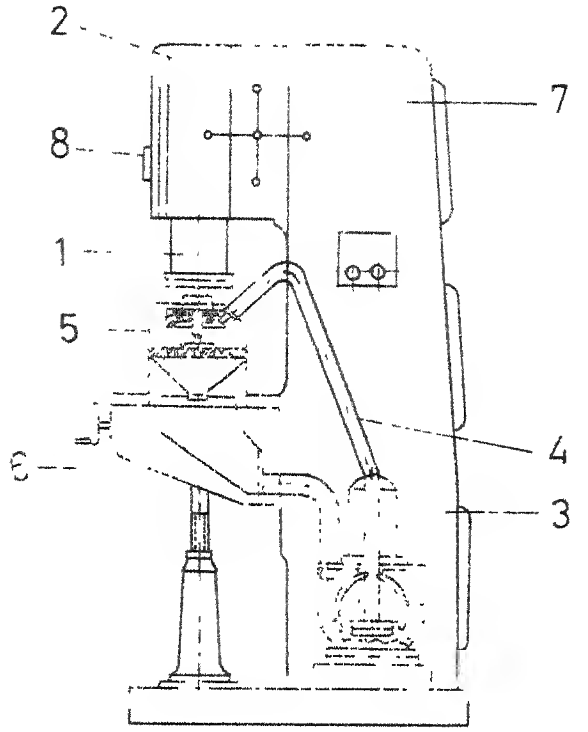
INTRODUCTION AND LITERATURE SURVEY

1.1 INTRODUCTION

Current techniques for mechanical working of materials are highly developed. Machine tools have been greatly improved in recent years to solve many of the varied and complex problems arising out of rapid advances in technology.

However, hard and brittle materials such as germanium, silcon, ferrites, ceramics, glass, quartz are difficult to machine because these materials often can not withstand high forces encountered in conventional machining processes. The need for machining these materials has led to the introduction of ultrasonic machining.

In ultrasonic machining, the material is removed by a tool vibrating with small amplitude of the order of 0.001" while abrasive slurry is supplied between the tool and the workpiece. The material is removed in the form of small particles. The total rate of removal is sufficient for practical purposes as there are large number of particles under the tool vibrating at frequencies of about 20-25 KCS. Thus



1. ACOUSTIC HEAD
2. FEED MECHANISM
3. ABRASIVE FEED PUMP
4. PIPES
5. JETS
6. TABLE
7. FRAME
8. POSITION INDICATOR

Set-up of ultrasonic mechine

FIG. 1

[redacted]

tool produces a cavity whose profile corresponds to that of the tool. Combinations of movements of the tool allow one to perform a variety of operations analogous to those of ordinary milling, shaping, profile milling on brittle materials. The abrasive also causes wear of the tool.

Current machines (Fig.1) have several specific features such as, an acoustic head, feed mechanism, abrasive feed system (including, pump, pipes and jet), and power source (not shown). In addition, there are features found in ordinary machine tools such as the table, frame and position indicator. The acoustic head contains the electromechanical converter, which drives the tool via a special holder (waveguide). The feed mechanism applies the necessary static force between tool and workpiece. The abrasive feed system continuously brings in fresh abrasive to the cutting area, removes metal particles and cools the tool and workpiece.

1.2 LITERATURE SURVEY

Miller (1) was the first to study the rate of cutting in ultrasonic machining. He assumed that the particles are embedded in the workpiece and tool by the applied force causing plastic deformation and work hardening of the material. The hardened portions are removed by chipping action.

[redacted]

This theory seems to be unjustified, because it assumes dependence of rate of material removal on work hardening which implies that the work material is plastic. However, most materials that are machined by ultrasonic machining are brittle.

Shaw (2) attributed the material removal, mainly, to two mechanisms, viz,

1. direct impact of the tool on grains in contact with the workpiece and
2. the impact of grains accelerated by the tool.

He gave an expression of depth of indentation as below

$$h = \left[\frac{8F_s y_o d}{\pi kHC(1+q)} \right]^{1/2}$$

where F_s static force

y_o amplitude of vibration of tool

q Ratio of hardness of the workpiece to that of the tool

C concentration of the abrasive slurry

k constant of proportionality.

This theory is based on a correct conception of the process as has been confirmed by subsequent experiments by Rozenberg (5) using high speed cinematography. However,

[redacted]

Shaw's theory does not agree with the experimental results regarding the effects of frequency, amplitude and force on material removal rate. Shaw assumed that all the particles are spherical in shape and take part in machining. In fact, the particles are irregular and only those large particles, which stand out above the small ones, take part in the material removal. The crushing of grains at high loads causes a fall in the rate of material removal. This effect is not taken into account in this theory.

Dikushin and Barke (3) related the energy consumed in removing the material from the workpiece to the amplitude and force of vibration using the laws of conservation of energy and momentum. They considered the vibration of the mass of the concentrator, from the end of the tool to the first displacement node of the concentrator assuming sinosoidal motion of the tool up to the time of contact. This theory did not predict quantitatively the material removal rate.

Kazantsev (4) took into account the non-uniformily in the grain size. He assumed that there are only some active grains with which the tool makes contact. Taking a linear relationship between the fraction of active grits and the ratio ($\delta/2R$) (where δ is the grain depth of indentation and R, the radius of grains taken as spheres), he derived an expression for the material removal rate. But his theoretical

[redacted]

results did not compare favourably with the experimental work done by others (5).

Rozenberg (5) gave a qualitative analysis of the nature of the damage in ultrasonic cutting. He assumed that the volume of damaged material is dependent on the maximal stress and the grain size. This means that the inhomogeneity in the grain size has a marked effect on the damage.

Kaczmarek, Kops and Shaw (6) deal with economics of ultrasonic machining. The considered the importance of the behaviour of the individual grains in the process, as the abrasive grains in the slurry constitute the actual machining elements. For a given charge of abras ive, the mean particle size is reduced with working time and the initially sharp edges become dull. This causes a decrease in the rate of material removal with time.

The longer the time between abrasive charges, the smaller will be the abrasive cost per unit volume removed. On the other hand, the cost of machine operator and overhead will increase as the rate of removal is decreased due to disintegration of abrasive particles. Considering these factors, they (6) proposed an expression for optimum abrasive replacement time.

W. Pentland and J.A. Kktermanis (7) gave some feasibility studies for improving ultrasonic machining rates.

[redacted]

They reported on the factors influencing material removal rate by considering the effects of cavitation, low temp, embrittlement of the work material, amplitude of tool vibration, grit size, method of application of slurry and heat treatment of the workpiece. Tool penetration rates were invariably highest for the annealed conditions, with lower rates for normalized and still lower rates for the oil quenched specimens. The finding is contrary to generally accepted practice for this process. Increases in removal rates of the order of 10 to 70% were obtained with 50°C increase in temperature of slurry using 240 and 400 grit abrasive slurries.

H.W. Baker (8) gave information about tool wear rates for different combinations of tool and workpiece material operating on glass, using a boron carbide abrasive the ratio of tool wear to stock removal is about 0.1% for tools made of tungsten carbide and about 1% for mild steel stools. When cutting lungsten carbide itself these figures are increased to 110 percent and 88 percent (8). He compared cutting speeds in various brittle materials , industrial ceramics and metals using boron carbide, silicon carbide and alumina as abrasives respectively. Machining rates were highest for baron carbide. He also compared machining rates for different grit sizes. Higher abrasive sizes gave higher machining rates.

[redacted]

J.R. Fredrick (9) compared cutting rates for different tool shapes. For glass as work material, and mild steel as tool material, he showed that machining rates were higher for a triangular base tool as compared to a circular tool. Also tool wear rates were less in a triangular base tool.

Literature survey shows that material removal rate depends on many factors such as amplitude and frequency of vibration of tool, static load, concentration and type and size of abrasive particles (4,5,6,8). Present work establishes functional relationship of machining rate with static load, concentration and time taking other factors constant.

Tool wear also depends upon above-mentioned factors (4,5,6,8). Normal practice is to give wear rate as a percentage of machining rate (8,9). A functional relationship of tool wear rate with static load, and concentration is established.

Machining rate relation thus obtained is used to find the optimal time after which tool should be replaced.

[redacted]

CHAPTER-II

TOOL REPLACEMENT CRITERIA IN ULTRASONIC MACHINING

2.1 INTRODUCTION

The tool is generally made from a tough material so that it does not chip easily. However, as a result of contact with the abrasive and cavitation effect, the tool also wears out appreciably. Most of the wear occurs at the end of the tool. However, the side wear is also significant, (about 10% of the end wear) (5) and affects the accuracy of the job. The longitudinal wear obtained in tools is found to be least for tough steels and greatest for brittle materials (8). The wear is not large if the workpiece is of glass, semiconductor, but it is very high for tungsten carbides. It is usual to specify the wear as a percentage of machining rate. With mild steel as tool material, wear rate as percentage of machining rate are

(i) 0.5 to 3 percent for germanium, silicon, ferrites, optical glass, soda glass and quartz

(ii) 12 percent for corundum

(iii) 50 percent for ruby

(iv) 70 percent for tungsten carbide, and

(v) 100 percent for hardened steel.

Side wear of tool introduces an additional effect of increasing the angle of the hole and rounding the sharp corners.

In ultrasonic machining, a resonant tool is designed in order to obtain sufficient amplitude at the tool tip. This is achieved by having a tool of length equal to half-wavelength or its multiple (5). It is known that as operation is continued the machining rate decreases with time (5,6). The factors that account for the decrease in machining rate with time are (5,6)

(a) likely reduction in size of abrasive particles due to crushing of grains (6)

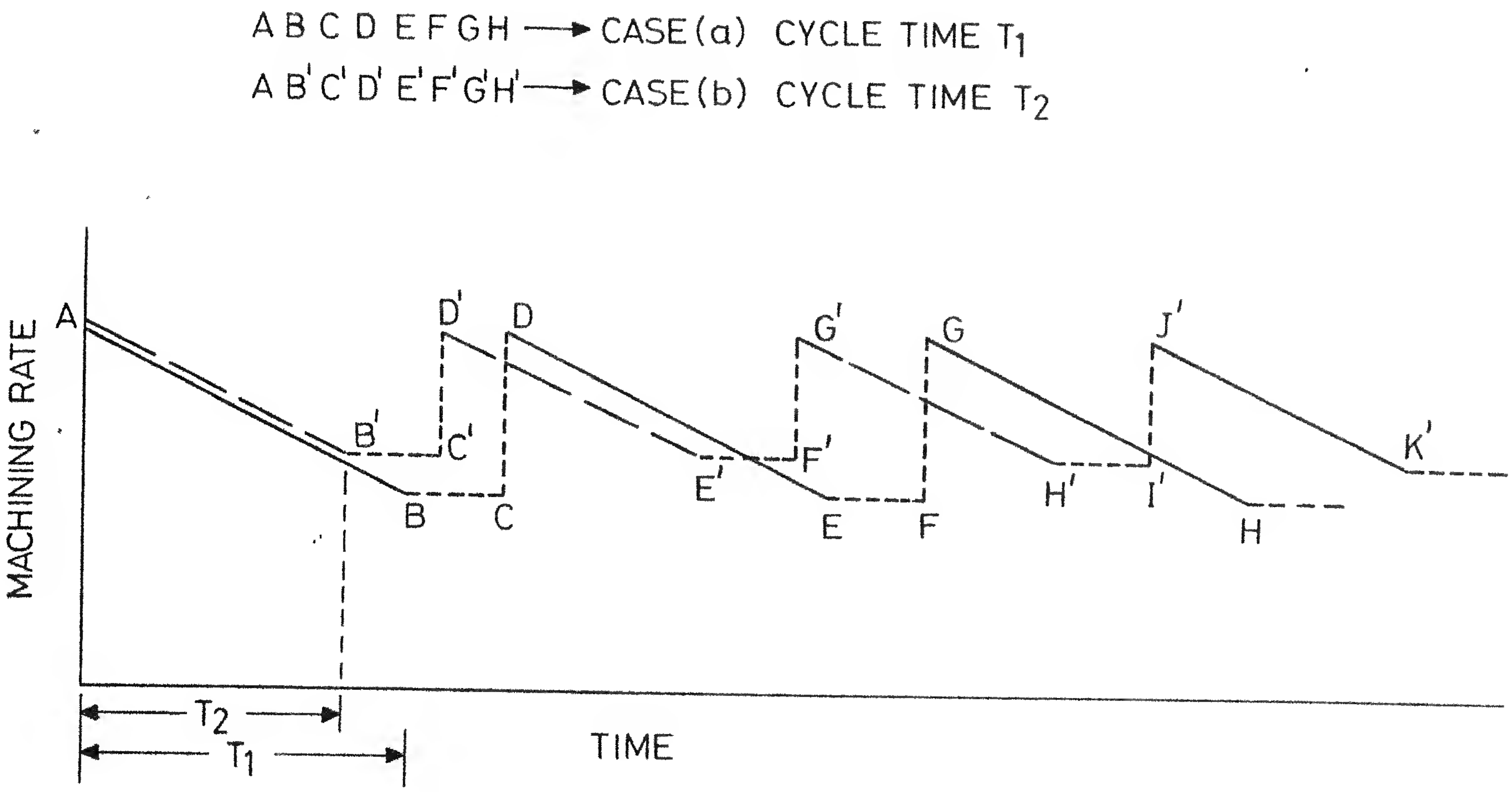
(b) likely reduction in amplitude of vibration due to shortening of length of the tool caused by tool wear, and

(c) departure of system from resonance conditions.

Thus with decreased machining rate, for a given job whole operation is going to take more time. In practice the tool is replaced when the side tool wear becomes excessive giving rise to unacceptable tapered holes. However, it is desirable to replace the tool before the machining rate falls to an uneconomical value. Economical tool replacement policy may be based on

(i) minimum cost criterion

(ii) maximum production rate criterion.



Tool replacement model

FIG. 2

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2.2 MODEL FOR TOOL REPLACEMENT

Tool replacement model is shown in Fig. 2. It is assumed that operation starts with a new tool and corresponding machining rate is at A. In case (a), after a cycle time of T_1, machining rate comes down to a value equal to B and it is decided to change the tool. B C represents tool replacement time. At D new tool comes into operation and same cycle is repeated. In case (b), after a cycle time of T_2, machining rate comes down to a value equal to B', when it is decided to change the tool. $B'C'$ represents tool replacement time. At D' new tool starts machining and same cycle is repeated. In the two cases discussed above total cost incurred is different, because of difference in cycle times. Present criteria develops a model to find out a value of T , after which tool should be replaced so that

(i) total cost incurred is minimum or

(ii) production rate is maximum.

Let

T be the time after which tool is to be replaced

N be the total number of jobs to be made

V be the volume removed in machining a hole in the job.

Total volume to be removed = N.V

Let machining rate be a function of time so that MR = $\phi(t)$

Volume removed per tool replacement cycle = $\int_0^T \phi(t)dt.A$

where A is the area of hole

$$\text{Number of cycles} = \left\lfloor \frac{N.\ V}{\int_0^T \phi(t)dt.A} + 1 \right\rfloor$$

$$= \lfloor n_r + 1 \rfloor$$

$$\text{where} \quad n_r = \frac{N.V}{\int_0^T \phi(t)dt.A}$$

Here the symbol $\lfloor x \rfloor$ represents lower integar of x.

Number of tools = $\lfloor n_r + 1 \rfloor$

Total time of operation = $n_r.T$

Tool replacement criteria may be based on

(i) Minimum cost criterion

(ii) Maximum production rate criterion

(i) <u>Minimum Cost Criterion</u>

It is known that the wear of tool is one of the causes of decrease in machining rate with time. If one continues to operate with a worn out tool, the whole operation will take a longer time. However, if it is decided to replace the tool, the costs of the new tool and tool replacement will be incurred. Minimum cost criterion provides an optimal balance of these costs.

Let

C_o be the cost of labour per unit time

C_e be the cost of a tool

t_{ch} be the time taken in replacing a tool

Then total cost C = cost of operation of machine + cost of tools + cost of tool replacement.

$$C = n_r * T * C_o + \left[n_r + 1\right] * C_e + \left[n_r + 1\right] * C_o * t_{ch} \qquad (2.2.1)$$

To get a value of T, minimising the total cost, the above function is differentiated with respect to T and equated to zero.

(ii) <u>Maximum Production Rate Criterion</u>

Time to machine one job will be equal to the time needed for actual machining plus the tool replacement time per job

$$\text{Time to machine one job} = \frac{n_r . T}{N} + \frac{\left[n_r + 1\right] V}{N} . t_{ch}$$

$$\text{Therefore, the production rate } Z = \frac{1}{\frac{n_r . T}{N} + \frac{\left[n_r + 1\right] t_{ch}}{N}} \qquad (2.2.2)$$

To maximise function Z, it is differentiated with respect to T and equated to zero.

CHAPTER-III

EXPERIMENTAL INVESTIGATION

Experiments have been conducted

(a) to develop a functional relationship of machining rate with load, concentration and time

(b) to develop tool replacement criteria.

The experiments are conducted on 200 watt Cavitron Drilling Machine. The ultrasonic transducer is driven by an oscillator and power amplifier at a resonating frequency of 25.5 KC. and an amplitude of 0.001". Soda glass is machined by using 1/2" dia tool made of mild steel. Emery (abrasive) of 120 mesh is used with water to form slurry for machining. Demineralised water is used for cooling purposes and for making slurry. Machining rates are found by noting the depths of tool penetration from a position indicator on the machine. Virtual depth cut is given by the tool penetration whereas actual depth cut (that is actual depth of hole drilled) is measured by a depth gauge.

Tool wear is measured by a microscope attached to the machine. Microscope is focussed on the tool before starting the operation and reading on the scale is noted.

After machining, the tool is brought back to the static position and reading of the scale on the microscope is noted again. Difference of the two readings gives tool wear during the time of operation.

Experiments are carried out at static loads of 0.476 Kg, 0.703 Kg, 0.812 Kg, 0.93 Kg. and concentrations of 0.125, 0.143, 0.167, 0.2 and 0.25. Concentration is taken as ratio of the volume of abrasive to the volumeof slurry with water. Each set of experiments is conducted by keeping the concentration constant and varying the load. The used slurry is removed from the system and fresh slurry is used for each load. The tests are done in increasing order of concentration to avoid the contamination of the slurry from any abrasive particles remaining in the system from the previous set.

CHAPTER-IV

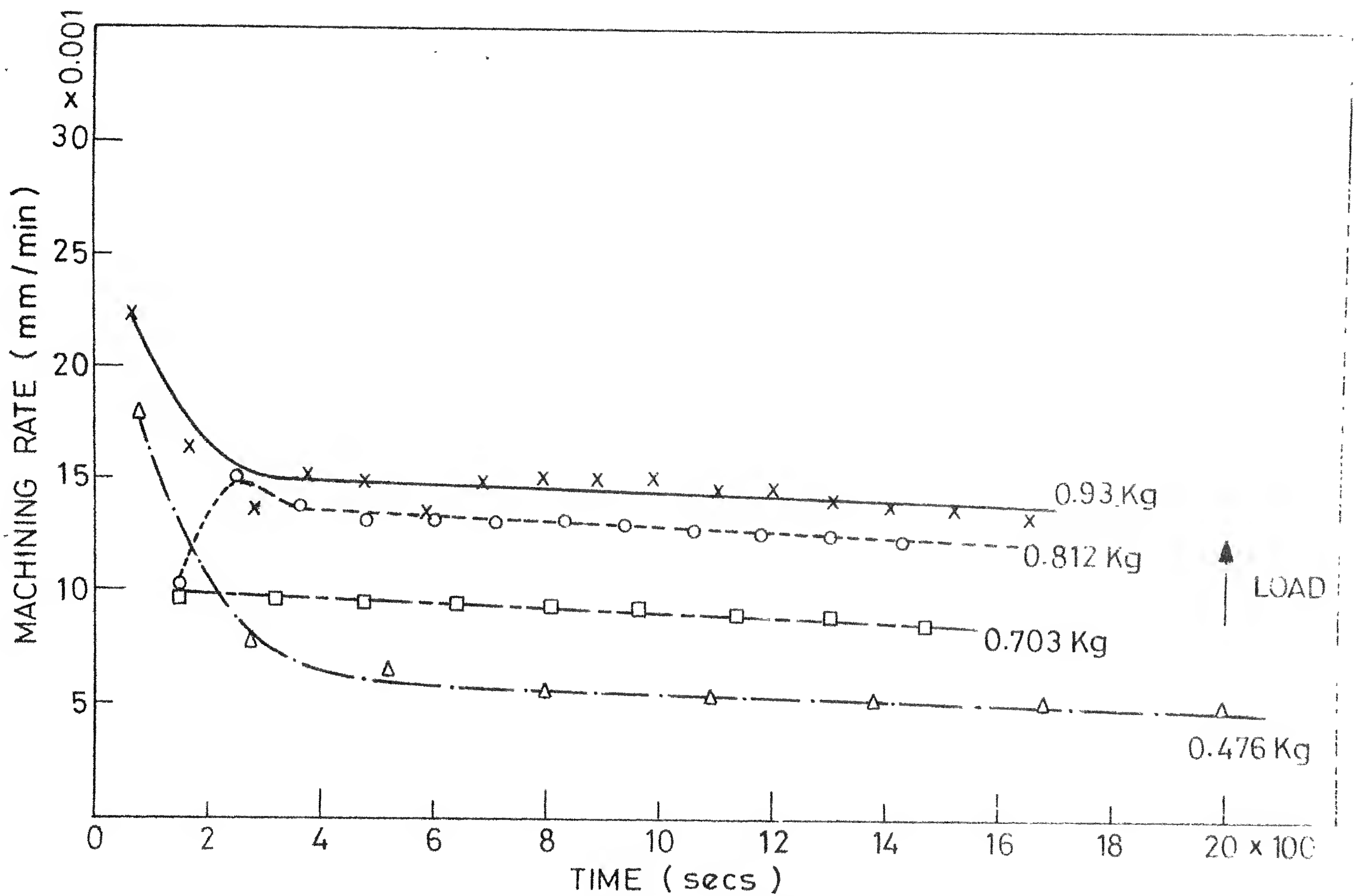
RESULTS AND DISCUSSIONS

4.1 VARIATION OF MACHINING RATE WITH LOAD, CONCENTRATION AND TIME

Figures 3 to 7 show variation of machining rate with time under different combinations of loads and concentrations. It is clear that in all the cases, system is in transitional state initially. In general, the machining rates decrease rapidly with time in the initial stages. However, in all the cases the variation of machining rate with time becomes linear after a maximum stablising time of 400 secs. The stablising time is different for different combinations of concentrations and loads.

The high value of indicated machining rate in the initial stages is explained with the help of Fig. 8. Fig. 8(a) corresponds to the initial position of tool. In Fig. 8(b), due to penetration of abrasive particles in the workpiece, the tool has come down and the position indicator reads A. However, as seen from Fig. 8(b), actual depth of cut (ADC) is zero whereas virtual depth of cut (VDC) is equal to A. Fig. 8(c) shows that after some machining the tool has moved down such that the actual depth cut is X and virtual depth cut indicated

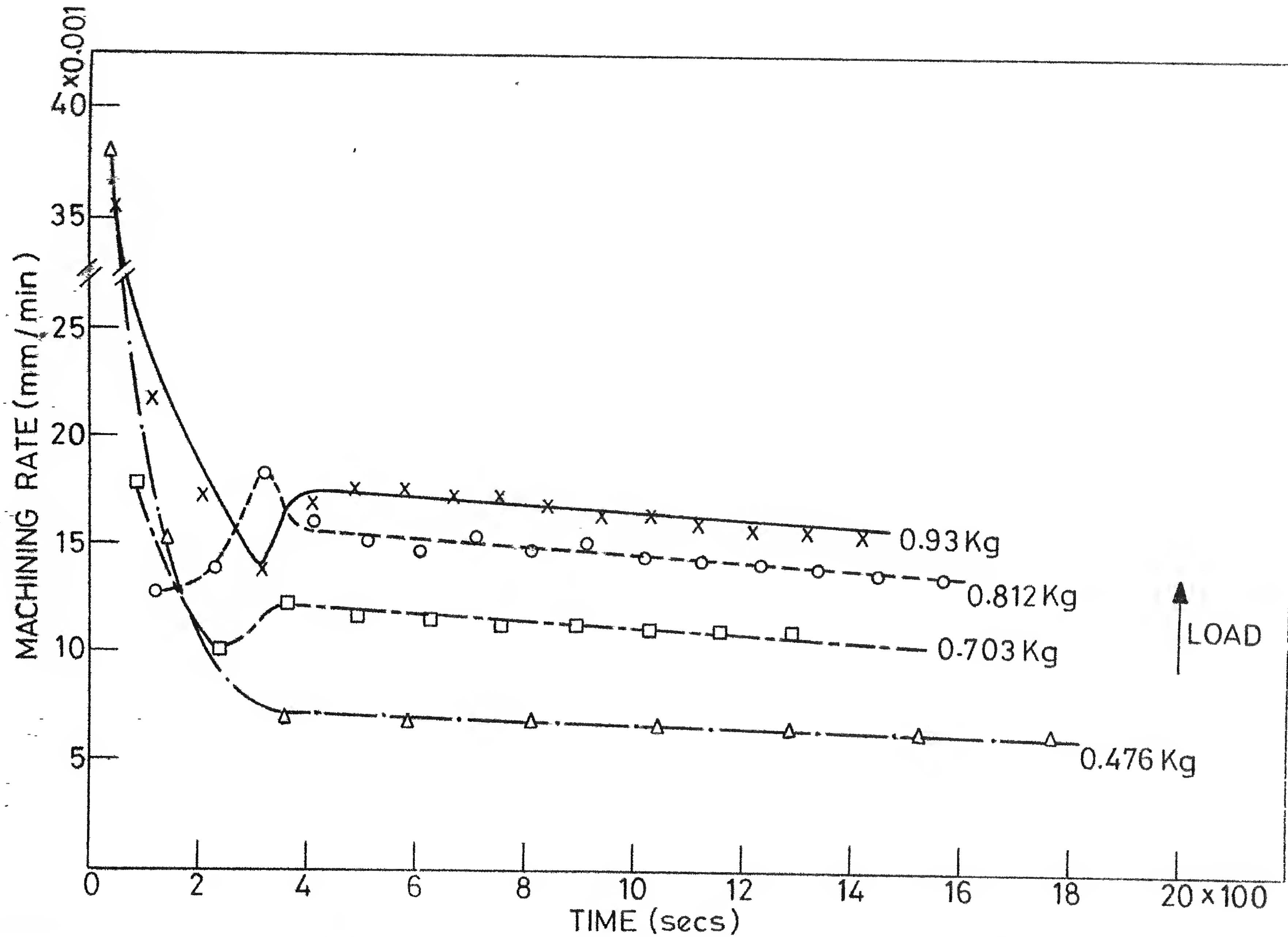
[redacted]



Variation of machining rate with time for various loads

CONCENTRATION 0.125

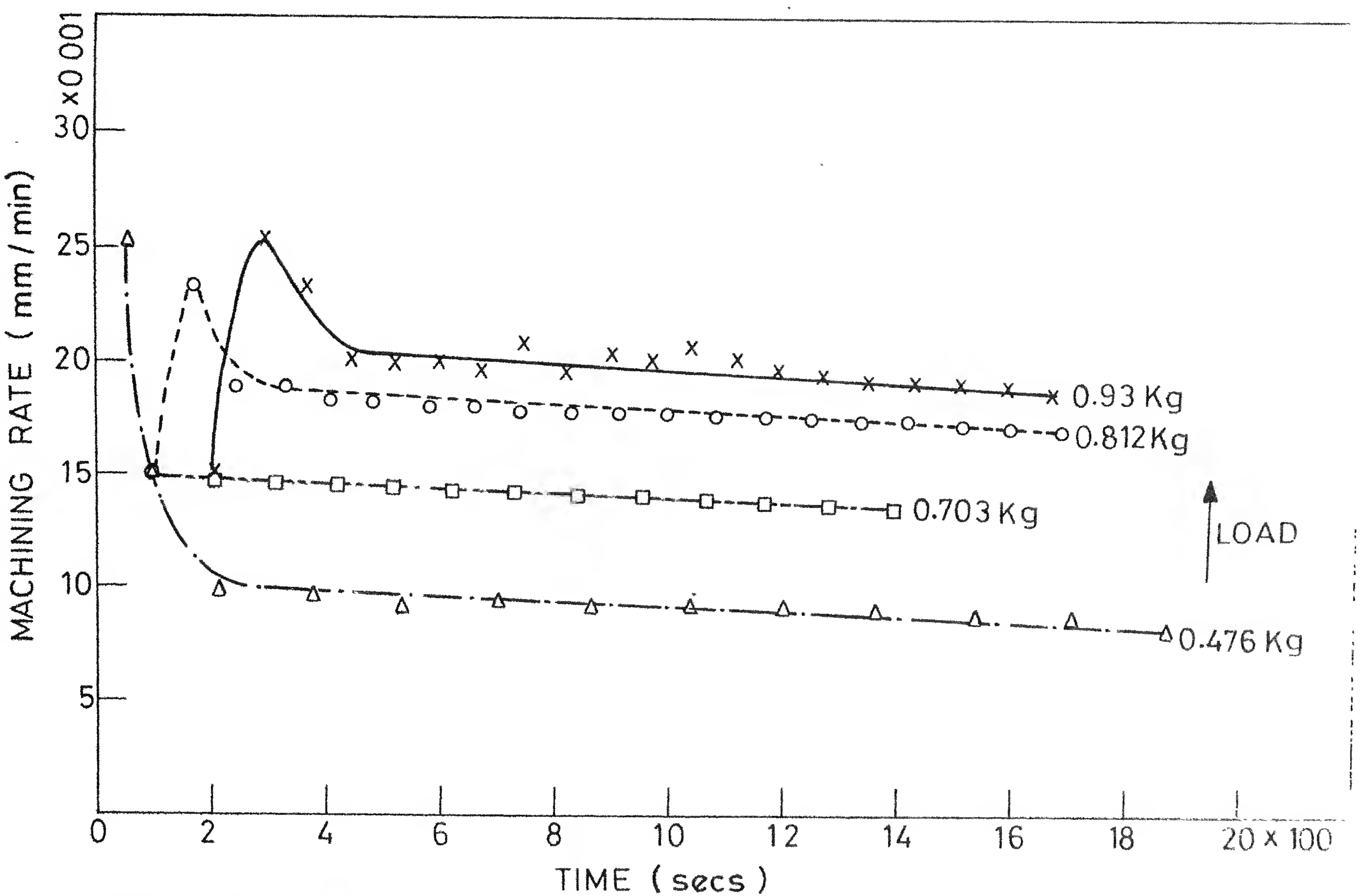
FIG. 3



... machining rate with time for various loads.

FIG. 4

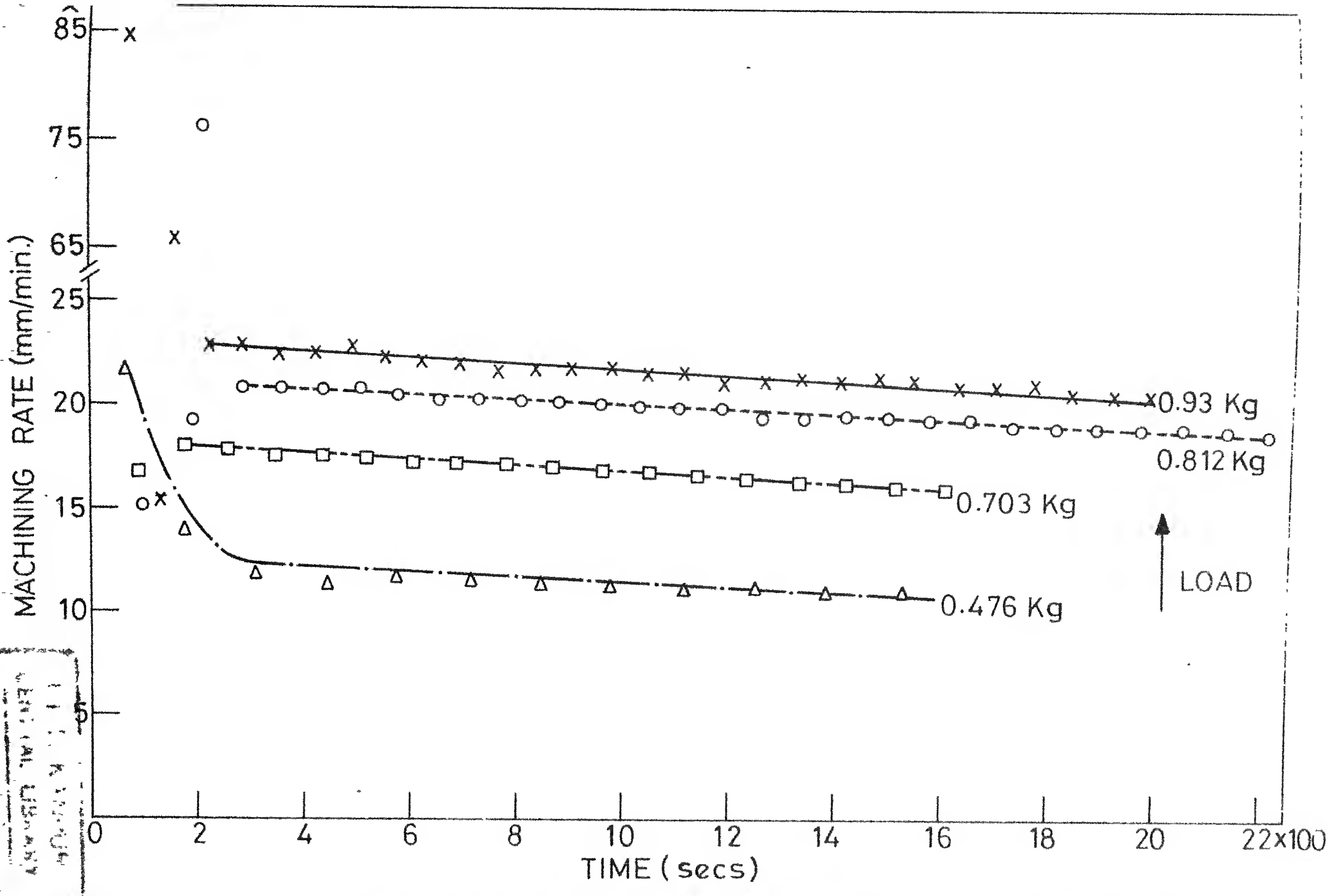
[redacted]



Variation of machining rate with time for various loads.

CONCENTRATION 0.167

FIG. 5

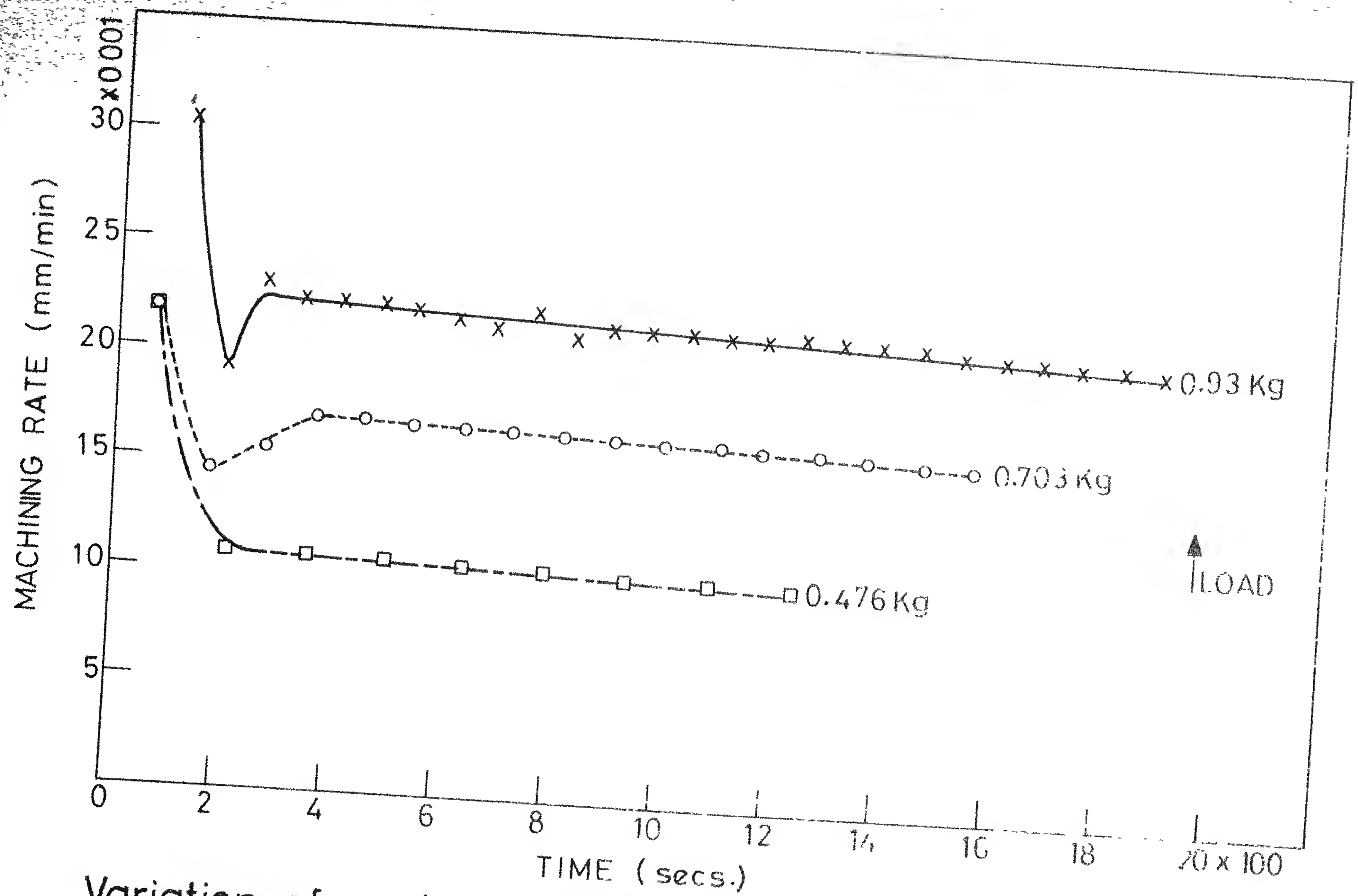


Variation of machining rate with time for various loads.

CONCENTRATION 0.200

FIG. 6

[redacted]

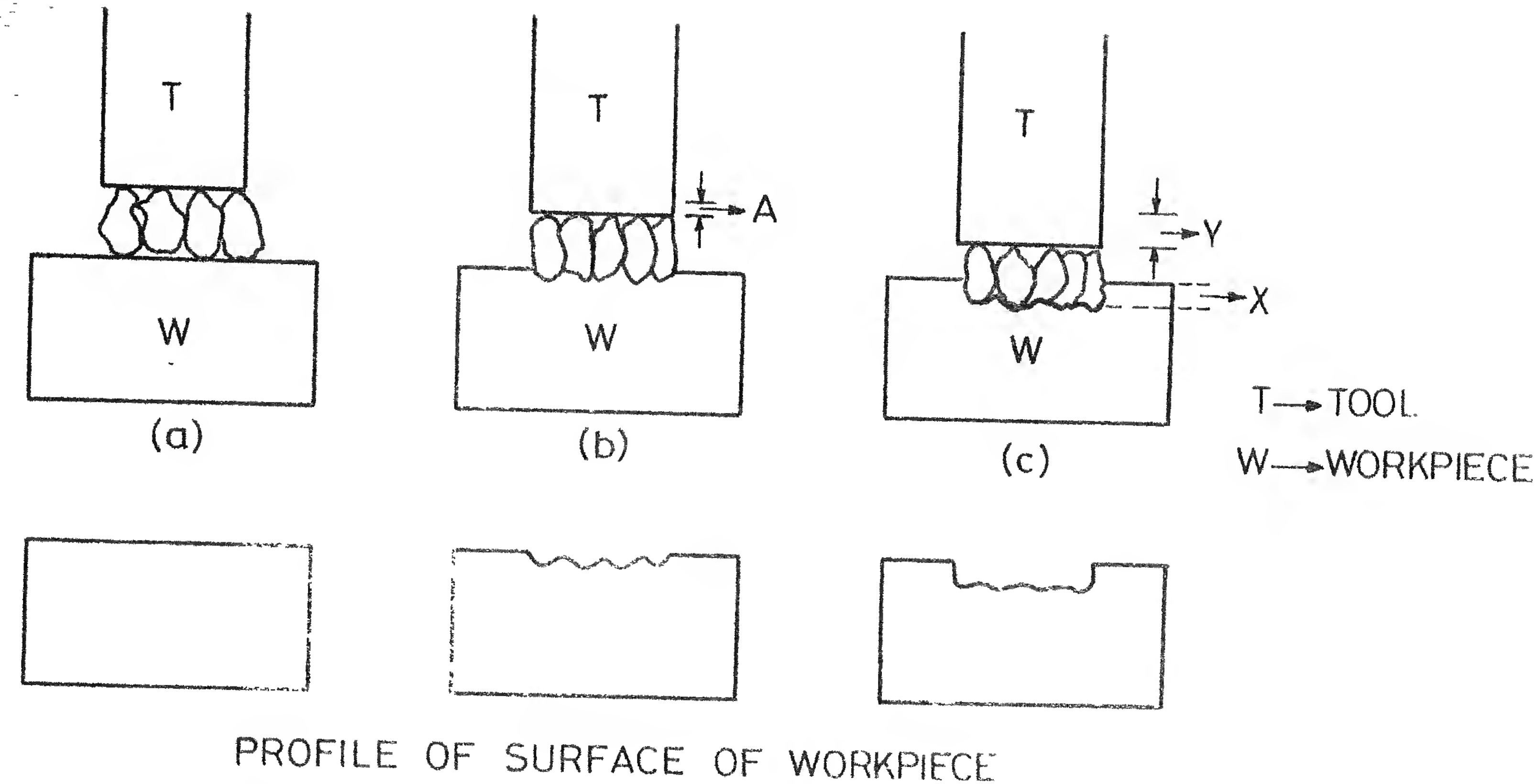


Variation of machining rate with time for various loads.

CONCENTRATION 0.25

FIG.7

[redacted]



Discrepancy in VDC and ADC due to initial plane surface of workpiece.

FIG.8

TABLE 1

LOAD(Kg) / CONCENTRATION	-	0.93	0.812	0.703	0.476
0.25	ADC(in)	.0256	-	0.0157	0.0086
	VDC(in)	0.027"	-	0.017	0.009"
0.2	ADC(in)	0.0272	0.0264	0.0162	0.0108
	VDC(in)	0.03	0.029	0.018	0.012
0.167	ADC(in)	0.0201	0.0189	0.0126	0.0106
	VDC(in	0.022	0.02	0.013	0.011
0.143	ADC(in)	0.0146	0.0141	0.0087	0.0079
	VDC(in)	0.016	0.015	0.01	0.009
0.125	ADC(in)	0.0157	0.0112	0.0086	0.0069
	VDC(in)	0.017"	0.012	0.009	0.008

[redacted]

by position indicator is Y. Obviously, VDC should be more than ADC. This difference was found to be more or less constant irrespective of time of operation, for a particular combination of load and concentration.

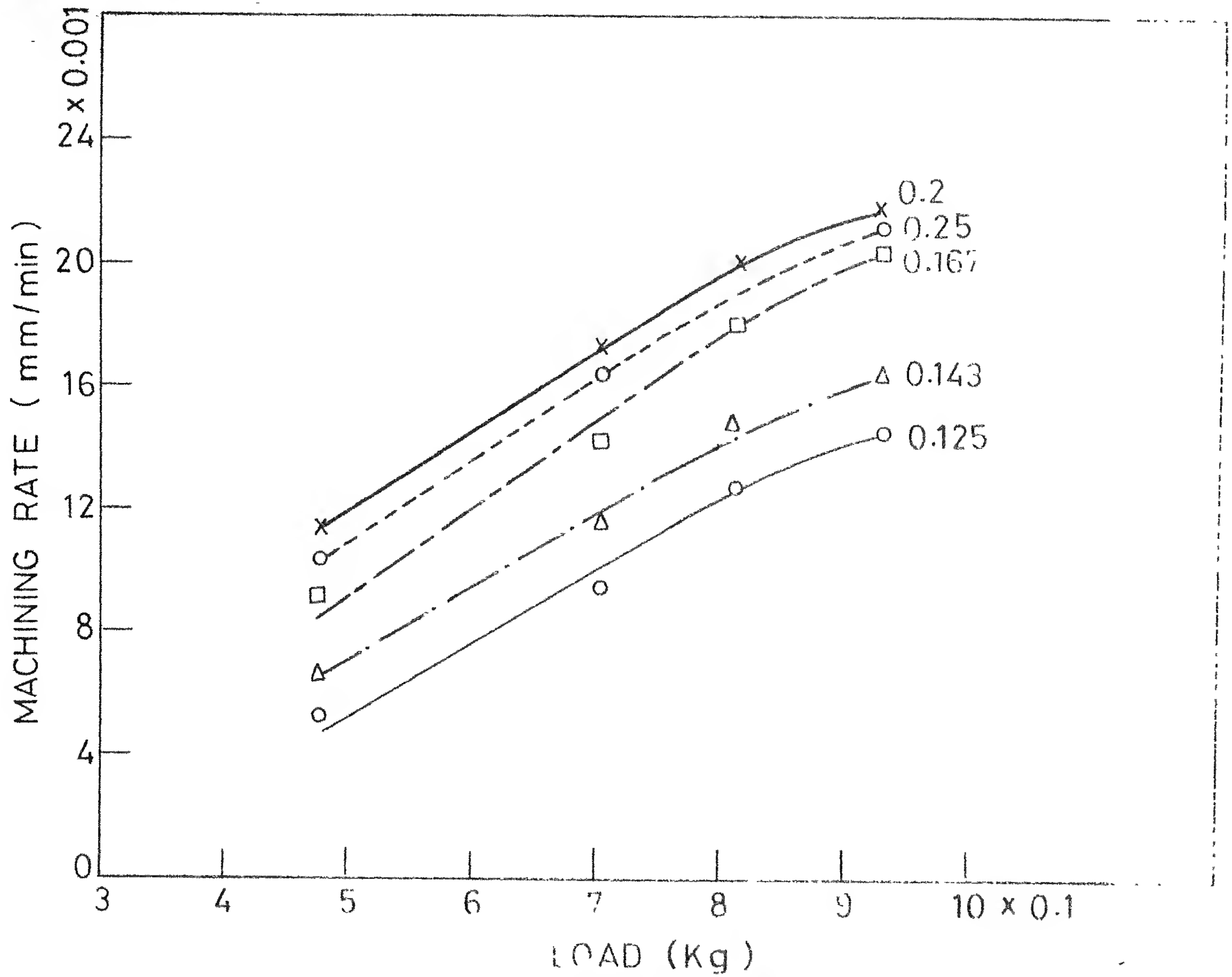
The experimental values of VDC and ADC are given in Table 1. Table 1 shows that actual depths cuts are less than virtual depths cut, which in turn implies that actual machining rate is less than virtual machining rate.

It is seen from Fig. 3 to 7 that rate of decrease of machining rate is not affected by load appreciably for all the concentrations investigated.

Fig. 9 shows that the variation of average machining rate with load is almost linear, with a little departure from linearity at higher loads for all the concentrations investigated. From Fig. 9 it is clear that as load increases, machining rate also increases for range of load tested. Actually the machining rate is known to drop beyond a certain value of load (5).

Fig. 10 shows the variation of average machining rate with concentration for various static loads. The average machining rate was calculated by ignoring the observations corresponding to transitional state. The figure shows that machining rate rises rapidly with concentration and reaches

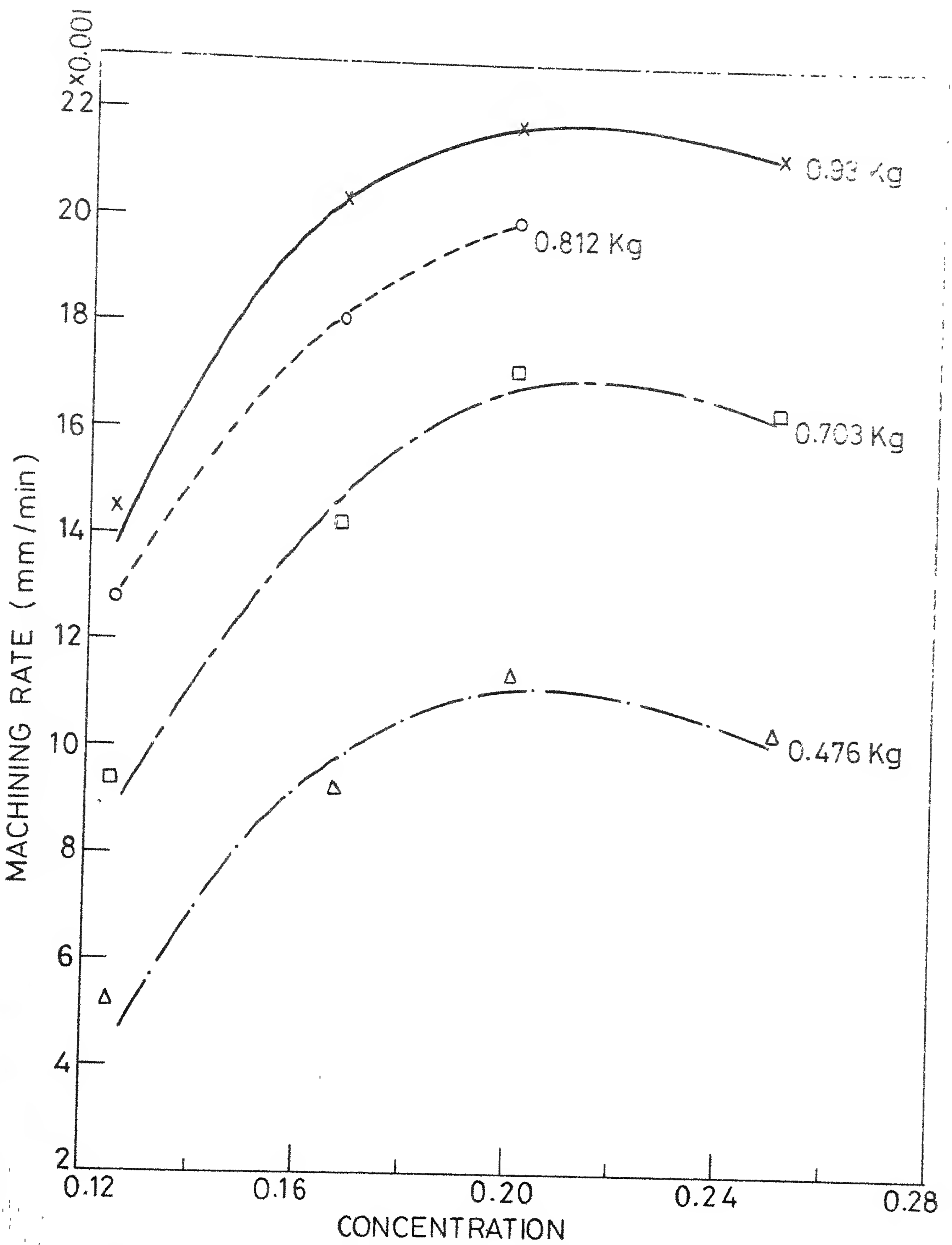
[redacted]



Variation of machining rate with load for various concentrations.

FIG. 9

[redacted]



Variation of machining rate with concentration for various loads.

FIG.10

[redacted]

its maximum value at a concentration of about 0.2 for all the loads tested. There is a little fall in machining rate beyond this value of concentration. This is due to the fact that as concentration is increased, the number of particles under the tool increases, which results in increased cutting rates. However there is an optimal value of concentration beyond which sputtering of particles under the tool becomes excessive. Therefore, even though the total number of particles in the slurry per unit volume is more at the concentrations higher than 0.2, actual number of particles under the load and taking part in cutting action are likely to be less, with consequent decreased machining rates.

4.2 FUNCTIONAL RELATIONSHIP IN ULTRASONIC MACHINING

A functional relationship expresses a dependent variable as a function of independent variables. In case of ultrasonic machining, machining rate is dependent variable and amplitude, frequency, load,concentration and type and size of abrasive particles are independent variables. Uptill now trial and error procedure is adopted to know machining rates for different combinations of these independent variable. However,it is desirable to have a relationship of machining rate with the above mentioned parameters, so that machining rates can be found out for any given combination of parameters. Generally,

[redacted]

optimal conditions of operations are specified for a machine, but sometimes it is not possible to operate under these conditions. Also it is not possible to specify optimal conditions for every possible type of job. Hence in all these cases, a functional relationship will be of great help.

For a given machine, it is difficult to change the amplitude of vibration. Amplitude of vibration of tool depends upon input signal given to transducer, which for a given machine is also constant. Transducers are designed for a particular resonating frequency (5, 9) and there is small permissible range in which frequency can be varied. Thus for a given machine these two factors are constant.. Out of the remaining four factors viz, load, concentration and type and size of abrasive particles, load and concentrations are the factors which are varied to obtain best machining conditions for a given job. Present work takes these two factors into consideration. The effect of time on machining rate has also been considered. Functional relationship for machining rate has been obtained by regression analysis for the experimental data. The regression analysis is based on minimising the sum of squares of residuals, where residual at a point is defined as the deviation of the fitted curve from the actual observation at that point.

[redacted]

Thus the machining rate (in mm/min.) is given by the expression,

$$MR = -2.84\times10^{-2} + 3.534\times10^{-2}L - 0.835\times10^{-2}L^2 + 1.112\times10^{-1}C$$
$$+ 6.108\times10^{-1}C^2 - 2.6212C^3 - .6\times10^{-3}t \qquad (4.2.1)$$

Here load L is in Kg., concentration C is by volume, time t is in minutes. Constant term ($-2.84\text{x}0^{-2}$) should not be intrepreted as the equation's intercept in the mathematical sense. Rather, it is to be interpreted as the mean effect on machining rate of all the excluded variables.

Relation (4.2.1) can be partially differentiated with respect to concentration and equated to zero to get optimal value of concentration so as to have

$$\frac{\partial MR}{\partial C} = 0.1112*C - 0.6108*2C - 3*2.6212*C^2 = 0$$

Solved by trial and error (2) gives optimal value of concentration as 0.22.

Similarly partial differentiation with respect to load gives

$$\frac{\partial MR}{\partial L} = 0.03534 - 2 \times 0.00835*L = 0 \qquad (4.2.2)$$

which gives load equal to 2.116 Kg. However, this value of load falls beyond the range of loads, we have investigated.

4.3 TOOL REPLACEMENT CRITERIA

For a given load and concentration, from equation (4.2.1), machining rate is related to time as $MR = K+C_1T$ ...

(4.3.1)

[redacted]

Where T is time in minutes

$$K = -\ 2.84*10^{-2}+3.534*10^{-2}L-0.835*10^{-2}L^2+1.112*10^{-1}C$$
$$+\ 6.108*10^{-1}C^2-2.6212C^3 \quad \ldots. \qquad (4.3.2)$$

Value of L and C can be substituted in (4.3.2) to obtain K.

$$C_1 = -\ 0.6*10^{-3}t$$

Substituting (4.3.1) in relation (2.2.1), cost function becomes

$$C = \frac{N.V.T.C_o}{\int_0^T (K+C_1T)dt.A} + \left[\frac{N.\ V}{\int_0^T (K+C_1T)dt.A} + 1\right]*C_e$$
$$+ \left[\frac{N.V.}{\int_0^T (K+C_1T)dt.A} + 1\right]*C_o*t_{ch}$$

This, when differentiated with respect to T and equated to zero, so as to minimise cost C, yields

$$T^2 + \frac{2\ (C_e+C_o*t_{ch})*T}{C_o} + \frac{2(KC_e+KC_o*t_{ch})}{C_1 C_o} = 0$$

Which can be solved for known values of C_e, C_o and t_{ch}, since K and C_1 are known.

Similarly substituting (4.3.1) in relation (2.2.2), production rate function becomes

$$Z = \left[\frac{n_r\ T}{N} + \frac{(n_r+1)\ t_{ch}}{N}\right]^{-1}$$

[redacted]

This when differentiated with respect to T and equated to zero so as to maximise production rate, yields

$$T^2 + 2\, t_{ch}\, T + \frac{2\, t_{ch}}{C_1}.K = 0$$

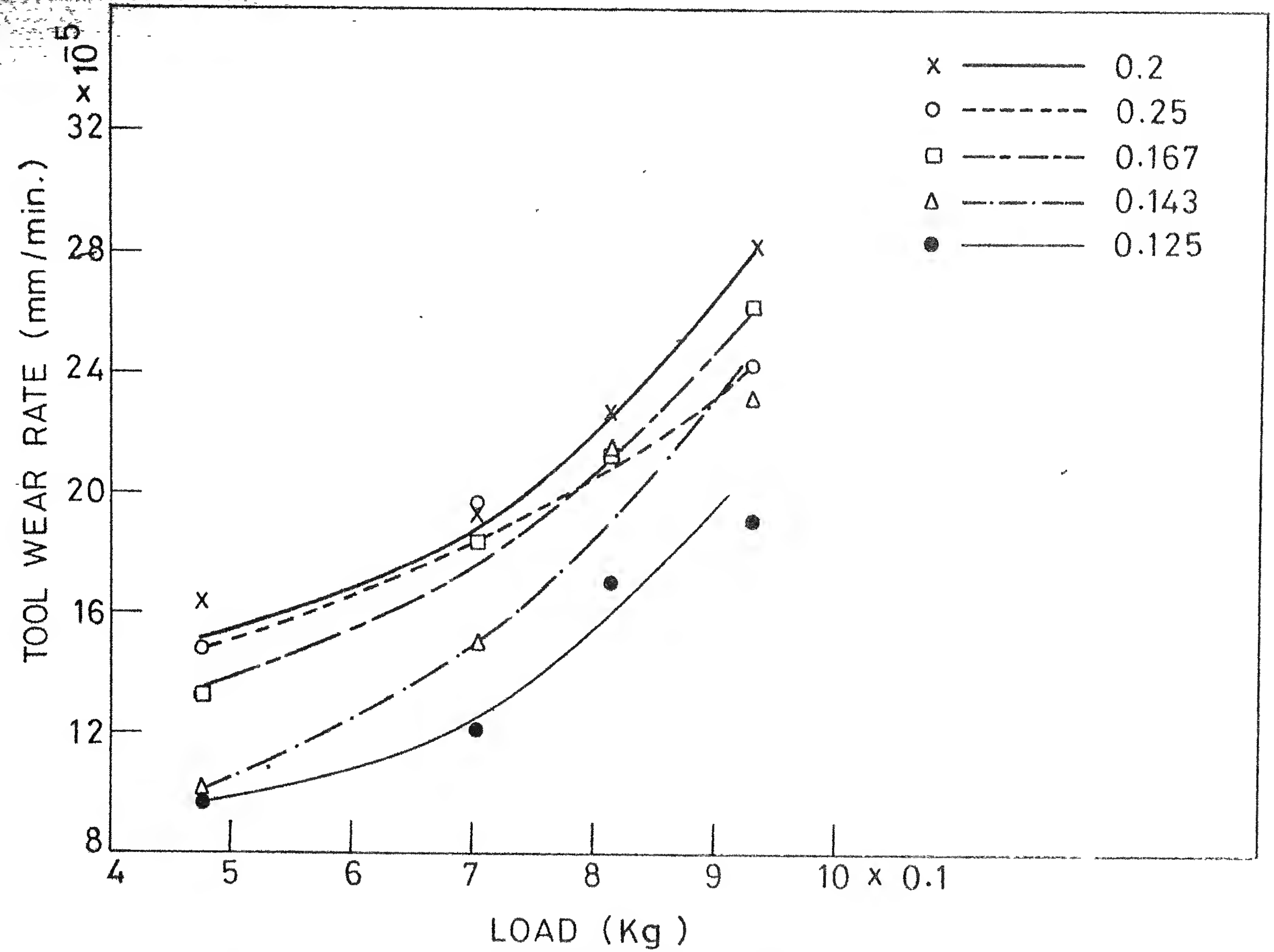
which can be solved for given value of t_{ch}, since K and C_1 are known.

4.4 TOOL WEAR

Tool wears out as a result of contact with the abrasive, cavitation is also known to effect the wear of tool. Fig. 11 shows variation of tool wear rate with load for different concentrations investigated. Tool wear rate increases with load and the rate of increase being higher for higher loads. It is desirable to operate at lower loads, if the tool wear rate is excessive.

Fig. 12 shows that the tool wear rate curve increases with increase in concentration and reaches its maximum value at about 0.2 concentration for all the loads. Furthermore, tool wear rate is not affected by concentration beyond the above value for all the loads except a load of 0.93 Kg., where the curve shows a significant decrease.

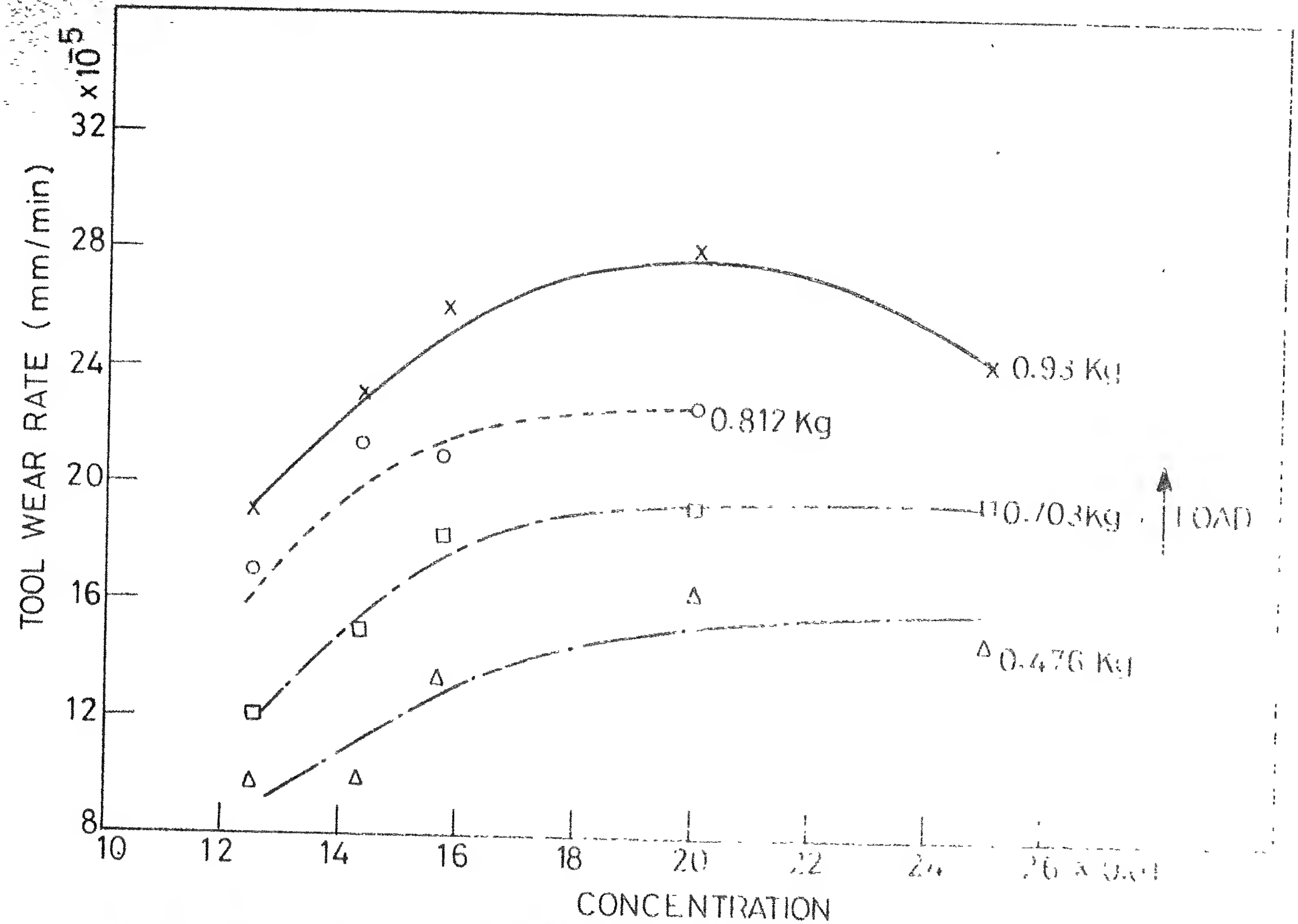
Time has little effect on tool wear rate. It is usual to express tool wear rate as a percentage of machining rate. In present case it varies from 0.5 to 1 percent of machining rate.



Variation of tool wear rate with load for various concentrations

FIG 11

[redacted]



Variation of tool wear rate with concentration for various loads.

FIG. 12

[redacted]

4.5 FUNCTIONAL RELATIONSHIP OF TWR IN ULTRASONIC MACHINING

TWR also depends upon the factors already mentioned while discussing relationship of machining rate with parameters of ultrasonic machining. It is desirable to express TWR also in terms of load and concentration, leaving other parameters because of reasons already given. Importance of this relationship may be visualized, if instead of tool replacement criteria discussed in the present work, policy is that tool should be changed, when it has worn out by a prespecified amount. In that case, for given working conditions, time of tool replacement can directly be calculated from (4.5.1).

$$TWR*100 = 4.67*10^{-2}-2.149*10^{-2}L+3.237*10^{-2}L^{2}-7.928*10^{-1}*C + 5.502*C^{2}-11.268*C^{3} \qquad (4.5.1)$$

Here load L is in Kg. and concentration C is by volume. Here constant term $4.67x10^{-2}$ is to be interpreted as the mean effect of all the excluded variables.

[redacted]

CHAPTER-V

5.1 CONCLUSIONS

Following conclusions are drawn from the experimental results:

(i) Relationship of machining rate (mm/min.) with load 'L' (Kg.), concentration 'C' and time 't' (min) is given as

$$MR = -2.84*10^{-2}+3.534*10^{-2}L-0.835*10^{-2}L^{2}+1.112*10^{-1}C + 6.108*10^{-1}C^{2}-2.6212C^{3}-0.6*10^{-3}t$$

(ii) Relationship of tool wear rate with load and concentration is given as

$$TWR*10^{2} = 4.67*10^{-2}-2.149*10^{-2}L+3.237*10^{-2}L^{2}-7.928*10^{-1}C + 5.502C^{2}-11.268C^{3}$$

(iii) Tool replacement criteria give optimal tool replacement time (T) as below

(a) For Minimum Cost Criterion

$$T^{2} + \frac{2(C_e+C_o*t_{ch})}{C_o}*T + \frac{2(KC_e+KC_o*t_{ch})}{CC_o} = 0$$

(b) For Maximum Production Rate Criterion

$$T^2 + 2t_{ch}T + \frac{2t_{ch}}{C_1}K = 0$$

where all the terms have already been explained.

SUGGESTIONS FOR FURTHER WORK

Functional relations obtained in the present work take account of load, concentration and time only. However, general relationships can be obtained if other parameters such as type and size of abrasive are also considered.

An alternate criteria for tool replacement policy may be based on wear of tool itself, that is, tool should be replaced when it has worn out by a prespecified amount. Once the amount is decided, relationship of tool wear rate with load and concentration can be used to find out tool replacement time.

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